NGL-05-003-272

# DIFFRACTION-LIMITED SPATIAL RESOLUTION OF CIRCUMSTELLAR DUST SHELLS AT 10 MICRONS


E.E. BLOEMHOF[1] and C.H. TOWNES[1]

Department of Physics
University of California, Berkeley

and

A.H.B. VANDERWYCK

Rockwell International Science Center
Thousand Oaks, CA




Suggested running title: CIRCUMSTELLAR DUST SHELLS

Received ____________________

(NASA-CR-173076) DIFFRACTION-LIMITED SPATIAL RESOLUTION OF CIRCUMSTELLAR SHELLS AT 10 MICRONS (California Univ.) 14 p HC A02/MF A01 CSCL 03B

N83-35974

Unclas
G3/90 15061

[1] Visiting observer at the Infrared Telescope Facility which is operated by the University of Hawaii under contract from the National Aeronautics and Space Administration.

## ABSTRACT

A new spatial array instrument has provided diffraction-limited mid-infrared intensity profiles of the type-M supergiant stars α Orionis and α Scorpii, both of which are known to exhibit excess 10 μm radiation due to the presence of circumstellar dust shells. In the case of α Ori, there is a marked asymmetry in the dust distribution, with peak intensity of dust emission a distance of 0.9" from the star.

## I. INTRODUCTION

The existence of a dust shell around the oxygen-rich supergiant $\alpha$ Orionis has been recognized for some time on the basis of photometric and spectrophotometric observations of a broad 10 μm emission feature attributed to silicates (Gillett, Merrill, and Stein 1971; Dyck et al. 1971; Merrill and Stein 1976). Substantial information on the spatial scale of dust distribution around $\alpha$ Ori has been provided by Michelson stellar interferometry (McCarthy, Low, and Howell 1977; Low 1979; Sutton et al. 1977). With a heterodyne spatial interferometer, Sutton et al. obtained a constant fringe visibility at 11 μm of 0.63 for projected baselines as short as 3 meters. Their results show that the circumstellar emission originates well away from the central star, at radii on the order of half an arcsecond, so that it is over-resolved at their interferometric fringe spacings. Their conclusion that dust produces 37% of the total 11 μm flux agrees with the result of Gillett et al. within the combined probable errors.

More recently, Howell, McCarthy, and Low (1981) have examined $\alpha$ Ori at 11.6 μm by scanning a focal-plane slit rapidly across the image and forming a power spectrum of spatial frequencies present in the brightness distribution. Interpretation of the resulting visibility function assumes circular symmetry and is somewhat model-dependent, but the data were found to be consistent with either a Gaussian circumstellar envelope of full width to 1/e points of 3.4", or a uniform disk of diameter 4.0".

Past observations of α Scorpii have been less extensive; however, a non-photospheric contribution equal to about 30% of the total 10 μm flux can be deduced from the spectrophotometry of Merrill and Stein (1976). Interferometric measurements made by Sutton et al. (1977) were restricted to high spatial frequencies by the southern declination of the source. These observations again completely over-resolved the circumstellar flux, which was found to agree in magnitude with the results of Merrill and Stein, and set a lower limit of about 0.24" for the inner radius of dust emission.

The present investigations were motivated by the fact that the size scale for circumstellar structure at 10 μm matches well with the diffraction limit of a 3-meter telescope, about 0.8". The wavelength dependence of seeing, which has been theoretically determined by Fried (1966) and experimentally confirmed by Boyd (1978), makes a 3-meter telescope diffraction-limited at 10 μm when the visible seeing is good. A reliable way to exploit this diffraction-limited resolution is to position in the focal plane an array of detectors whose individual fields of view are defined by their small size, rather than by instrumental apertures, and to scan the image over the array faster than atmospheric changes. The single-detector intensity profiles thus obtained do not depend on any normalization of the relative responsivities of separate detector elements or amplifier channels, and so can give reliable indications of small-scale structure around the photospheric intensity peak.

## II. INSTRUMENTATION

The observations reported in this paper were made with a new instrument utilizing an array of sensitive HgCdTe photodiode detectors of dimension 100 μm. The array chip was made as part of an ongoing program at Rockwell to

develop backside-illuminated detector-array/silicon-CCD hybrids (Shin et al. 1980). For the purposes of our instrument, the chip is mounted in a hardwired flatpack and only twenty-five contiguous detector elements, arranged in the shape of a cross, are accessed. Each of these elements is connected to its own AC-coupled amplifier characterized by a smoothing time-constant of about 3 ms. Repeated readouts of the amplifiers are made as the earth's rotation carries the source of interest through the field of view of a stationary telescope. Each detector element then provides an intensity profile of the source in which right ascension relative to the bright photospheric component of the star is determined by the accurately-known diurnal rate (about 15" per second). Readouts of a given detector are separated by 2.5 ms of time, and pairs of consecutive readouts are co-added, so stored samples are separated by 5 ms; this interval corresponds to about 0.075" cos ($\delta$) of right ascension, where $\delta$ is the declination of the source. We will refer to the detector whose declination exactly intercepts the position of the stellar photosphere as the "central" detector.

The instrument is mounted at the Cassegrain focus, and the telescope beam is guided onto the detector array through oversize baffles by plane-mirror optics. There are no spurious diffraction effects beyond the Airy pattern of the telescope, and no attenuation of the high spatial frequencies of the source brightness distribution by instrumental slits or apertures. An optical bandwidth of 2 μm is provided by the combination of detector cut-off at about 10.3 μm and a coated-germanium interference filter with a cut-on at 8.3 μm; this bandwidth includes the peak of the 10 μm silicate emission feature.

## III. OBSERVATIONS

The measurements reported here were obtained on 1983 February 24 at the Infrared Telescope Facility (IRTF), NASA's 3-meter telescope on Mauna Kea, under conditions of good seeing. The scale size at the IRTF Cassegrain is such that each detector element covered a 0.2"x0.2" square of the focal plane. The IRTF is a rather stable telescope, and the relatively slow beam at Cassegrain (f/37) was an observational advantage, as it implied a relatively generous depth of focus. Even so, it was found that the telescope focus required frequent adjustment to meet our requirement for a diffraction-limited image.

The time series of samples obtained from individual detectors were digitally filtered to remove an electrical pickup component at about 80 Hz. On many data sets this component was very small, in which case the data were little affected by the post-processing. The non-zero Fourier coefficients due to the 80 Hz pickup were well separated from the non-zero coefficients due to source structure, which had frequencies of about 25 Hz and below.

The solid line in Figure 1 shows the intensity profile to be expected when a monochromatic 9 μm point source passes directly through the field of view of one of the detectors. The curve is calculated from diffraction theory, and includes the effects of obscuration of the telescope's primary aperture by the seconday mirror. The data points in Figure 1 show the corresponding profile actually observed for α Bootis, a type-K star that has no infrared excess and is expected to be essentially a point source at 10 μm. To obtain the data points, the central-detector profiles from three separate drift-scans through the source were normalized to equal peak intensity and then averaged; the dotted lines trace the 1-sigma error

limits of this averaging procedure. Comparison of the two profiles shows that the true point-spread function of the telescope with our 2 μm bandwidth is well described by an Airy pattern with an effective wavelength near 9 μm, at least as far as the photospheric image is concerned. The signal-to-noise ratio on α Bootis (which is a dimmer 10 μm source than α Orionis and α Scorpii by factors of 5 and 2.5 respectively) is sufficient to detect structure as faint as the secondary maxima of the Airy pattern on a single sweep through the star.

Figure 2a shows the central-detector intensity profile of α Ori obtained by applying the averaging procedure described above to the three best-focus data sets, as judged by width of the main peak. The width of the resulting profile's main peak is consistent with a diffraction-limited image of the point-like stellar photosphere. The subsidiary peaks give evidence for spatially extended continuum radiation; further, this extended radiation is asymmetrical, being more intense to the west of the central star than to the east. The three best-focus data sets were selected from about 20 scans through the source performed over a period of more than an hour at various focal settings and telescope declinations. In every data set except one, the dust structure shows an enhancement on the west side of the object, similar to that seen in figure 2a; the main difference in scans which are close to focus is a variation in the intensity of the main photospheric peak compared to that of the extended dust peaks. In the one exceptional case, the extended brightness was slightly greater on the east side of the source. This data set, however, showed clear signs of being out of focus or distorted by imperfect seeing: in addition to having an excessively wide main peak, there was blurring between the main peak and the subsidiary peaks of the profile.

Figure 2b shows the central-detector intensity profile of $\alpha$ Sco; in this case, one scan was in much better focus than the others we obtained, and this scan is presented alone. There is evidence for extended infrared radiation, as the empty-sky level labeled zero is quite flat on both sides of the source, though this is not shown in the Figure. Also, as in the case of $\alpha$ Ori, the secondary maxima are more intense and closer to the main peak than would be expected for a point source; dust emission can easily provide such a pattern. The dust emission appears to be less intense per unit solid angle than that around $\alpha$ Ori, more symmetric, and probably more extended.

Two-dimensional displays of the $\alpha$ Ori data give some indication of additional extended structure in the form of a dust peak just over an arcsecond to the north of the photosphere and a less marked enhancement of dust emission to the southeast. However, these indications of north-south structure are not conclusive for two reasons. First, the focus which optimizes the north-south shape of the point-spread function may not coincide with the best focus chosen on the basis of east-west profiles, if the optical system has any astigmatism (and while astigmatism alone would not produce such asymmetries, the image becomes rather sensitive to other slight optical imperfections when it is out of focus). Second, accurate interpretation of north-south structure requires accurate calibration of the relative gains of separate detector channels, which is not assured in the case of these observations.

## IV. DISCUSSION

The present observations are consistent with some but not all of the results derived from past interferometric measurements. In both α Ori and α Sco, the peak dust emission appears to occur approximately 0.9" from the star. In α Ori, valleys between the main peak and the dust peaks indicate that the dust density drops rapidly closer to the star and may not be substantial within 0.5", or 20 stellar radii. This is consistent with the conclusion of Sutton et al., from interferometric data, that there is very little radiation from dust inside of 12 stellar radii. The effective outer diameter of the dust radiation is, from Figure 2a, approximately 2.5". While a difference in wavelengths used here and in the slit-scanning technique of Howell et al. may account for some difference in apparent diameters, the values derived from that experiment are somewhat too large to agree with the present results. A shell of dust emission 0.9" from the photosphere, averaging 10% of its intensity as seen by our detectors, would provide a total flux approximately equal to that of the photosphere. Hence, the subsidary peaks observed here are consistent with the total dust emission previously found.

The asymmetry detected in the circumstellar shell of α Ori emphasizes the importance of replacing visibility data with direct brightness distribution maps whenever possible. While a two-element interferometer which does not retain phase information can detect asymmetries corresponding to an elliptical source shape, it is not sensitive to an asymmetry with respect to reflection, such as that displayed by Figure 2a.

There have been extensive efforts to model the outer atmospheres of late-types stars, and that of $\alpha$ Ori in particular (see, for example, Jura and Morris 1981). As yet, all of these have made the basic assumption of spherical symmetry. However, there has been some experimental evidence for non-uniformity and asymmetry from large-beam measurement of flux variation (Forrest, Gillett, and Stein 1972) and polarization (Dyck et al. 1971). Moreover, from theoretical considerations, Salpeter (1974) has suggested that dust formation may be facilitated by the presence of cool patches and instabilities in stellar atmospheres, while Schwarzschild (1975) has proposed that large convection cells in red giant photospheres may produce asymmetries in dust distribution. The asymmetries we have observed are consistent with emission on the scale of one or a few photospheric convection cells, in agreement with Schwarzschild's proposal. It has previously been difficult to understand how circumstellar material is ejected from late-type stars (cf. Zuckerman 1980); the distribution around $\alpha$ Ori suggests that localized and temporary instabilities are involved, rather than simpler spherical steady-state mass flows. While it is not yet clear what fraction of red giants produce highly asymmetric dust distributions, the present observations raise questions about the validity of details of calculations using models of high symmetry for any case in which such symmetry is not established.

This work was supported in part by NASA grant NGL 05-003-272. The authors thank the staff of the Infrared Telescope Facility for facilitating the observational work. We are grateful to Walt Fitelson for his expert assistance with the electronics, without which the successful construction of the array instrument would not have been possible.

## REFERENCES


Boyd, R.W. 1978, J. Opt. Soc. Am., 68, 877.

Dyck, H.M., Forrest, W.J., Gillett, F.C., Stein, W.A., Gehrz, R.D., Woolf, N.J., and Shawl, S.J. 1971, Ap. J., 165, 57.

Forrest, W.J., Gillett, F.C., and Stein, W.A. 1972, Ap. J. (Letters), 178, L129.

Fried, D.L. 1966, J. Opt. Soc. Am., 56, 1372.

Gillett, F.C., Merrill, K.M., and Stein, W.A. 1971, Ap. J., 164, 83.

Howell, R.R., McCarthy, D.W., and Low, F.J. 1981, Ap. J. (Letters), 251, L21.

Jura, M., and Morris, M. 1981, Ap. J., 251, 181.

Low, F.J. 1979, in IAU Colloquium 50, High Angular Resolution Stellar Interferometry, ed. J. Davis and W.J. Tango (Sydney: Chatterton Astronomy Department, School of Physics, University of Sydney), p. 15-1.

McCarthy, D.W., Low, F.J., and Howell, R. 1977, Ap. J. (Letters), 214, L85.

Merrill, K.M., and Stein, W.A. 1976, Pub. A.S.P., 88, 285.

Salpeter, E.E. 1974, Ap. J., 193, 585.

Schwarzschild, M. 1975, Ap. J., 195, 137.

Shin, S.H., Vanderwyck, A.H.B., Kim, J.C., and Cheung, D.T. 1980, Appl. Phys. Lett., 37, 402.

Sutton, E.C., Storey, J.W.V., Betz, A.L., Townes, C.H., and Spears, D.L. 1977, Ap. J. (Letters), 217, L97.

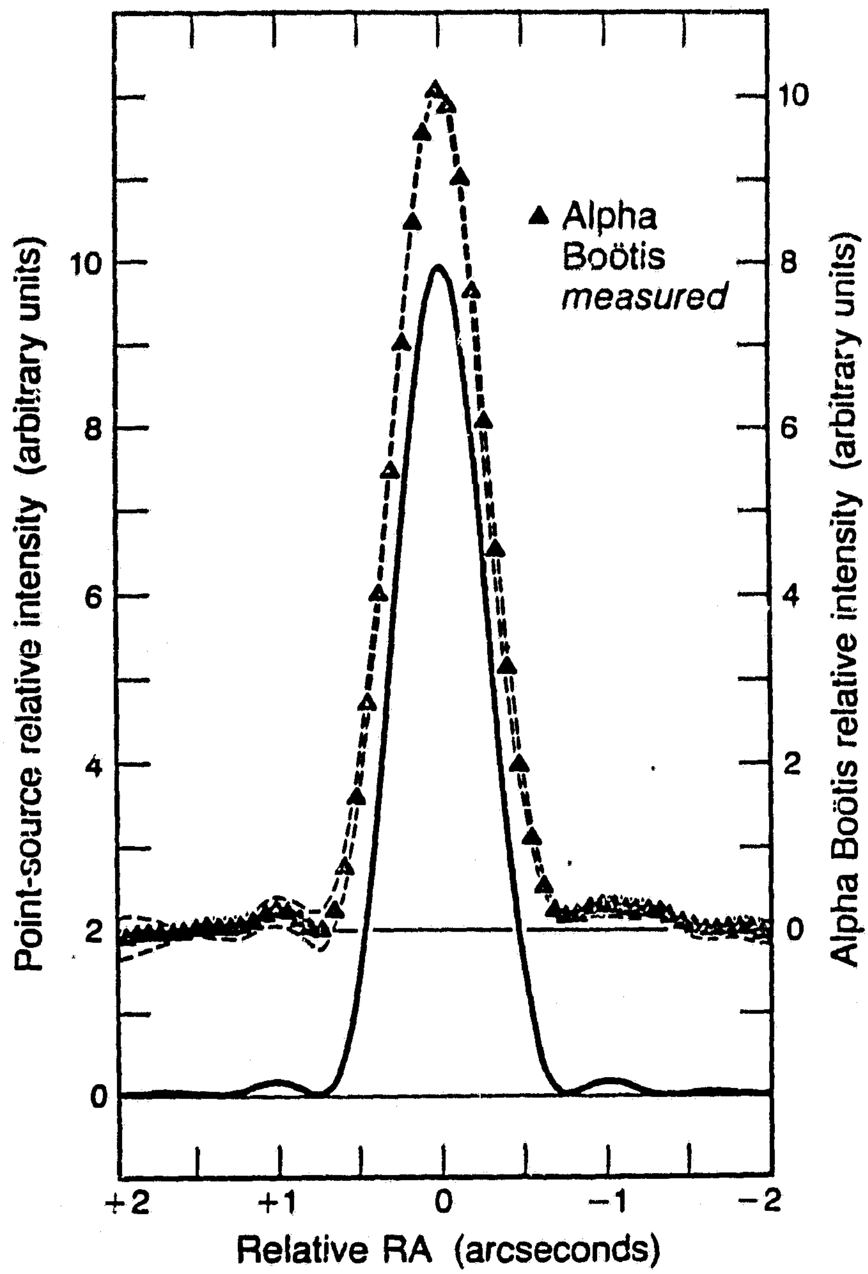
Zuckerman 1980, Ann. Rev. Astron. Astrophys., 18, 263.

# FIGURE CAPTIONS

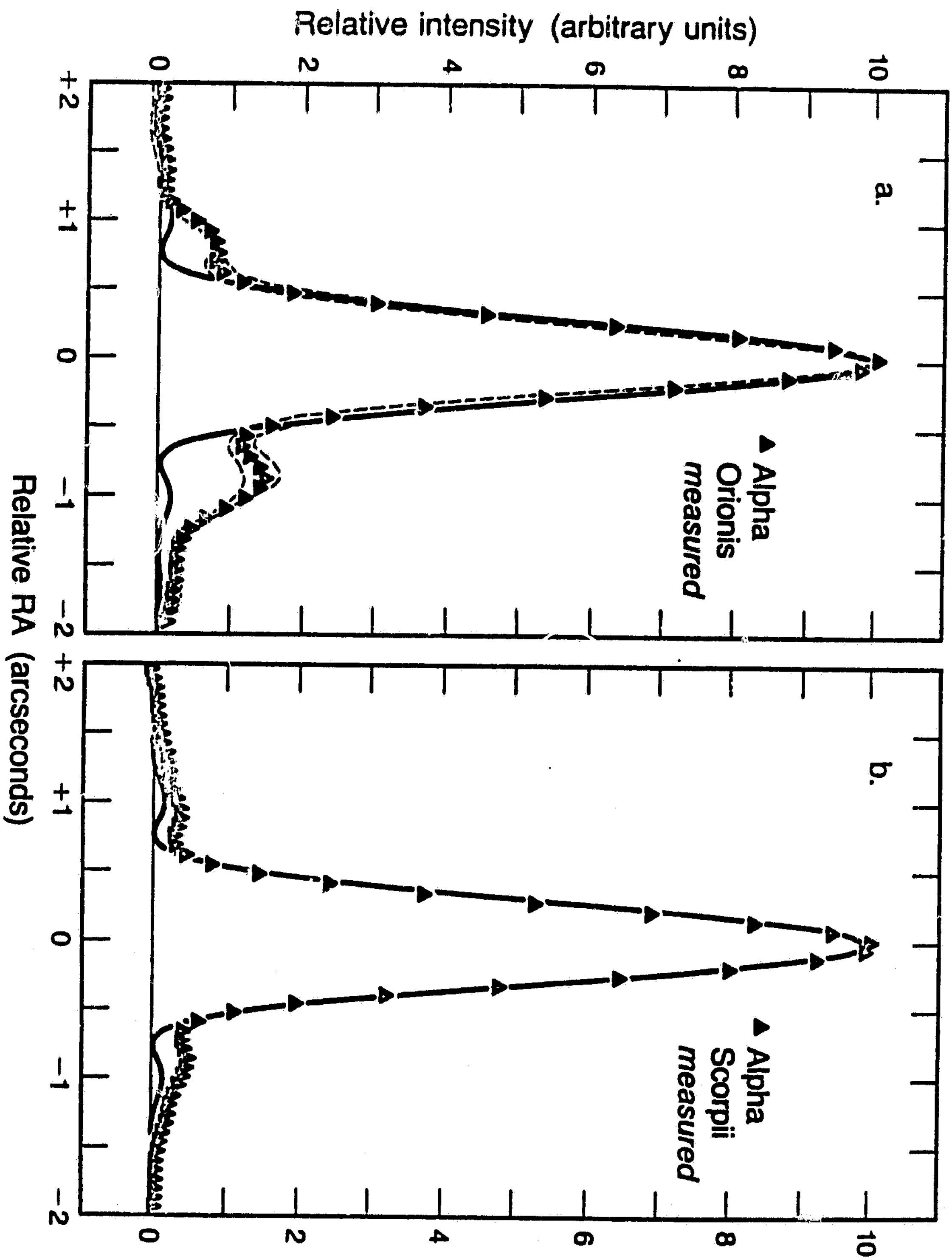
FIG. 1. Profiles of telescope point-spread function as seen by a detector passing directly through the position of a point source. Solid line is the theoretical curve (Airy pattern) for a monochromatic 9 μm point source. Data points (offset for clarity) are the measured east-west profile through α Bootis (average of three scans). Dashed curves are 1-sigma error limits. α Bootis is believed to have negligible dust emission, and hence to be effectively a point source. The main peaks of the two profiles are virtually identical.

FIG. 2. Profiles of supergiant stars with circumstellar dust shells (data points), superimposed on the theoretical point-spread function of Figure 1 (solid line). (a) Measured east-west profile through α Orionis (average of three scans). Dashed curves are 1-sigma error limits. (b) Measured east-west profile through α Scorpii (single best-focus scan).

ORIGINAL PAGE IS
OF POOR QUALITY



ORIGINAL PAGE IS
OF POOR QUALITY



E.E. BLOEMHOF and C.H. TOWNES: Department of Physics, University of California, Berkeley, CA 94720

A.H.B. VANDERWYCK: Rockwell International Science Center, Thousand Oaks, CA 91360